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13. ABSTRACT (Maximum 200 words) The primary objective of this project was to develop a reliable means for measurement or estimation of the in-situ geostatic lateral stress from the results of cone penetration and/or other in-situ tests. The research included analytical studies, laboratory tests on several sands, and field tests. There were two related studies - one on the causes of the aging sands and the effects of aging on properties, and the other on direct prediction of liquefaction resistance using cone penetration test measurements. the detailed research results are contained in five Ph.D. dissertations that were completed as a part of this project.					
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**HORIZONTAL STRESS IN-SITU BY CONE PENETROMETER
AND RELATED STUDIES**

Final Report

by

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November 20, 1992

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I. STATEMENT OF PROBLEM

The in-situ stress state of a soil has a profound influence on its stress-deformation and strength properties. While the vertical stress is ordinarily easily determined, accurate measurement or computation of the horizontal stress has not been possible. The primary objective of the research on this project was the development of a reliable means of measurement or estimation of the in-situ geostatic stress from the results of cone penetration (CPT) and/or other in-situ tests. The research has included two related studies, one on the causes of the aging of sands and the effects of aging on mechanical properties, and the other on direct prediction of liquefaction resistance using cone penetration test measurements. The research program was funded concurrently and about equally by the Army Research Office and the National Science Foundation.

II. SUMMARY OF MOST IMPORTANT RESULTS

The most significant results include: (1) the development of a methodology for the estimation of in-situ horizontal stress from the sleeve friction measured during a cone penetration test, Masood (1990), Masood and Mitchell (1993), (2) development of a method for prediction of cone penetration resistance from the stress-deformation and strength properties of a sand, Salgado (1993), (3) the development of a methodology for the estimation of the liquefaction resistance of a sand on the basis of cone penetration resistance without the need for cross-correlation between the cone penetration resistance and the Standard Penetration Test penetration resistance, Tseng (1989), Mitchell and Tseng (1990), and (4) rational analysis, based on cavity expansion theory, for the quantification of calibration chamber size effects on the measured cone penetration resistance, Sisson (1990). Salgado (1993).

The project benefitted greatly by the opportunity to undertake field in-situ tests in Vancouver with colleagues from the University of British Columbia, and in Oslo and Drammen, Norway with colleagues from the Norwegian Geotechnical Institute and the Norwegian Transportation and Road Research Laboratory. There was extensive collaboration during 1991 and 1992 with Professor Michele Jamiolkowski of the Polytechnic University of Turin, Italy, who arranged for full access to the extensive CPT data base accumulated by the ENEL-CRIS and ISMES laboratories in Milan and Bergamo, Italy. The results of more than 200 carefully controlled calibration chamber tests on sands of different types and at different states were made available to us for testing of theories and methods developed as a part of this project.

In the aftermath of the Loma Prieta Earthquake of October 17, 1989, which struck at about the middle of the project period, extensive field testing was done at several sites in the San Francisco Bay Area which underwent liquefaction. The test data are available for further evaluation of the in-situ lateral stress prediction and CPT-based liquefaction prediction methodologies developed as a part of this project.

and this work is continuing.

Four Ph.D. dissertations were completed by students supported on his project, and one additional Ph.D. dissertation will be completed by early 1993. Abstracts of each of these dissertations are reproduced below, as they provide more detailed summaries of the research results.

A. Determination of Lateral Earth Pressure in Soils by In-Situ Measurement, by Tahir Masood (1990)

The in-situ stress state of a soil plays a key role in the design and construction of many civil engineering projects. In-situ testing methods provide rapid and economical means of estimating the stress state in a variety of soils. The objective of this research was to investigate reliable and accurate means for estimating the lateral stresses in the ground using easily applied in-situ soil testing techniques.

A number of in-situ testing methods used for estimation of the lateral stresses were reviewed. Of these methods, the dilatometer test, the lateral stress sensing cone penetration test, and the stepped blade test were selected for further study due to their simplicity and cost effectiveness. A method for estimating the lateral stress from sleeve friction measured during a CPT was also developed which appeared very promising when evaluated using existing CPT data.

Accurate assessment of the vertical thrust required to push the dilatometer into the ground is essential for making accurate estimates of the lateral stresses from a DMT. The dilatometer used during this research was modified to measure a continuous profile of penetration resistance during a test.

A number of laboratory calibration chamber (CC) tests were performed with the dilatometer and the lateral stress sensing cone penetrometer (LSSCP) on Monterey #0 and Ticino sands. These tests were used to evaluate the existing correlations and develop new correlations for estimation of the lateral stresses. Data from the LSSCP tests were also used to evaluate further the sleeve friction method for estimating the lateral stresses.

A number of field tests were performed with the dilatometer, the LSSCP, and the stepped blade at various well-documented sites. Data from the field tests were used to evaluate the existing and newly developed correlations (from the laboratory CC tests). Suitability, accuracy, reliability and simplicity of the three in-situ methods were also studied.

The method for estimating in-situ lateral stresses from measured sleeve friction gave results of reasonable accuracy in a variety of soil types. The reliability of this method is dependent on the measured sleeve friction and

overconsolidation ratio (OCR) of the soil. A method for estimating OCR of cohesive soils from a CPT, as described in this thesis, gave very good results. In cohesionless soils, the LSSCP and DMT were equally accurate and reliable for estimation of in-situ lateral stresses. The LSSCP could be very cost-effective due to the high rate of testing that is possible (i.e. four to five times faster than with a DMT). The stepped blade is more suitable for soft cohesive soils. Use of the blade in stiff soils may result in severe damage to the equipment.

B. Lateral Stresses on Displacement Penetrometers, by Richard Craig Sisson (1990)

In-situ stresses are important in the analysis of many geotechnical engineering problems. One recently developed approach for determining horizontal in-situ stress is to measure lateral stress on the shaft of a Cone Penetrometer. However, because displacements and stress changes occur in soil around a penetrometer, a relationship is required to interpret in-situ stresses from measured stresses.

No theory was found suitable to predict stresses around penetrometers. therefore, experimental methods were used to confirm and expand existing empirical interpretation techniques for the measured horizontal stress.

Previous studies showed that laboratory penetration tests using large samples in pressure chambers may be affected by sample boundary conditions, and perhaps cone size. Tests to investigate these matters were conducted on Monterey No. 0 sand using two sizes of penetrometers in two different diameter chambers having constant stress boundaries. Test results indicate that penetration resistance decreases with decreasing ratio of chamber diameter to penetrometer diameter, and that boundary effects are similar to those predicted by cavity expansion theory for finite cylinders. Penetration resistance may decrease slightly with penetrometer diameter.

Laboratory calibration tests were also performed on SRS7 sand, which is more compressible than Monterey No. 0 sand. In addition, there are temperature and axial force effects on the lateral stress measurement section. Results showed that increased compressibility gave reduced tip resistance. The ratio of measured lateral stress to boundary stress for SRS7 sand was in the same range as for Monterey No. 0 sand and increased with increasing relative density in a similar manner. However, further study is required because only a limited number of tests on SRS7 were performed.

Closely spaced field penetration tests using four sizes of penetrometers indicated that tip resistance and measured lateral stress are reasonably repeatable measurements. Penetration resistance varied with cone size near strata boundaries, but no cone size effect was noted away from boundaries. The empirical correlation developed from laboratory tests was used to

estimate in-situ lateral stress from the lateral stress measured on one of the field penetrometers. Results for sandy soils mostly fell in a reasonable range, but were too high in some layers.

C. Analysis of Penetration Resistance and Determination of the Stress State in Sands, by Rodrigo Salgado (1993)

A theory of cone penetration resistance has been developed that is based on (1) cavity expansion analysis, from which a cavity limit pressure is obtained, and (2) a stress rotation analysis, which allows the computation of penetration resistance from the limit pressure. The soil is assumed non-linear in both the elastic and plastic ranges, and the analysis is applicable to cavity expansion or penetration both in calibration chambers and in the field. The input parameters for the analysis are the relative density D_R of the soil, the horizontal and vertical effective stress σ'_h and σ'_v , the constant-volume or critical state friction angle ϕ_c , a value or a correlation for the low-strain shear modulus G_0 , cone (or pressuremeter) diameter, and, if the analysis is to be performed for a calibration chamber, the diameter of the chamber. Values for "average" shear modulus G and friction angle ϕ to be used in models that assume equivalent linear elasticity and perfect plasticity are by-products of the analysis.

The theory has been verified by comparing predicted results with those of over six hundred cone penetrometer and pressuremeter calibration chamber tests. It is used in the evaluation of chamber size and boundary effects, which are the source of great difficulty in transposing results obtained for a soil in a calibration chamber to those to be expected for the same soil in the field.

Knowledge of relative density D_R and the stress state (σ_v, σ_h) at every point in a sand mass is required for the most reliable geotechnical designs. As deep penetration resistance, as measured by the cone penetrometer point resistance q_c , and the low-strain shear modulus G_0 (obtained indirectly from measurements of shear wave velocity V_s), are two quantities that depend fundamentally on relative density and stress state, use of the new theory of penetration resistance and a correlation for low-strain shear modulus permits working backward from measurements of q_c and V_s to determine D_R and σ_h with good accuracy. A method previously proposed for determination of σ_h from penetrometer sleeve friction f_s is also evaluated.

The penetration resistance theory is applied to the determination of the tip resistance of piles and drilled shafts, quantities that depend strongly on in-situ stress state and relative density. Bearing capacity factors in terms of lateral earth pressure coefficient and relative density are supplied in convenient graph and table forms to aid in the calculations.

D. Prediction of Cone Penetration Resistance and Its Application to Liquefaction Assessment, by Dar-Jen Tseng (1989)

The need to assess the liquefaction potential of sandy soil deposits is crucial to the safe and economical design of many civil engineering projects. While the cone penetration test (CPT) has been adopted worldwide as an economical and efficient in-situ test for many site investigations and types of geotechnical design, few data are available at the present time to enable development of a direct correlation between cone resistance and liquefaction resistance. The main objective of this study, therefore, was to derive such a correlation. This correlation is based on the assumption that the factors that increase the liquefaction resistance of a given soil also increase the cone resistance.

A cone resistance prediction method based on the cavity expansion theory was developed. In order to account for nonlinear soil deformation behavior and the limited sample sizes used in calibration chamber tests, some modifications were made to the cavity expansion method proposed by Keaveny (1985). The modifications included: (1) development of a solution for a finite soil mass, (2) the assumption of a nonlinearly elastic soil outside the plastic sheared zone around the cone tip, and (3) that the shape of the expanding cavity created by the penetrometer was a combination of a sphere and a cylinder. Thus the ultimate pressure required for expanding a cavity was assumed to be an average of the pressures to expand spherical and cylindrical cavities. A numerical scheme was adopted to compute the ultimate cavity expansion pressures iteratively, and a finite element program was written to serve this purpose. Chamber cone penetration test results were used to validate cone resistance prediction method for four different sands, namely, Monterey #0 sand, Ticino sand, Hokksund sand, and Sacramento river sand.

A direct correlation between the predicted cone resistances and liquefaction resistance was derived from the results of cyclic load tests on the same sands. Available field data consistent with the proposed correlation.

The in-situ horizontal stress is as important as the vertical stress for the development of cone penetration resistance. Thus, a parallel effort was carried out during this research program to improve our ability to measure the in-situ horizontal stress. The design of a lateral stress sensing cone penetrometer developed by Huntsman (1985) at the University of California, Berkeley was modified to improve its durability for field tests. A limited number of chamber tests with this new penetrometer have given good results.

E. Time Dependent Property Changes of Freshly Deposited or Densified Sands, by Christine Anne Human (1992)

Many deposits of clean sand have been found to show an increase in

stiffness and strength with time both in the field and in the laboratory. This phenomenon is known as "aging". The changes can take place over a period of weeks to months and are therefore of significance to the geotechnical engineer. In this thesis a comprehensive review of the published case histories is presented. However, it was found that due to the variability and uncertainty in the data, it is not possible to draw unambiguous conclusions about the rate and magnitude of aging.

Three different techniques are tested to quantify the rate and magnitude of aging, and to elucidate the underlying mechanisms. The methods are the measurement of electrical conductivity with time, the measurement of shear wave velocity in a triaxial cell with time and the measurement of the cone tip resistance in the laboratory, using a mini penetrometer. Of these methods, the measurement of shear wave velocity appears to produce the most reliable and reproducible results. Unfortunately, there is no clear evidence to determine whether the mechanisms responsible for aging are either mechanical or chemical in origin, and our ideas on the underlying mechanisms remain speculative. However, the results from the tests which were performed as a part of this research tend to suggest that for Crystal Silica sand, grain rearrangement and interlocking at particle contacts occur in the laboratory during aging, although bond formation at particle contacts cannot be excluded.

A field study conducted at a site which had liquefied during the 1989 Loma Prieta earthquake, shows that a sand deposit, disturbed by a large earthquake, may show an increase in both the cone tip resistance and the sleeve friction with time. The testing also illustrates the difficulty of drawing conclusions from an hydraulic fill site which is naturally very variable.

III. LIST OF PUBLICATIONS

Human, C. A. (1992), "Time Dependent Property Changes of Freshly Deposited or Densified Sands," Ph.D. Dissertation in Civil Engineering, University of California, Berkeley

Masood, T. and Mitchell, J. K. (1993), "Estimation of In-Situ Lateral Stresses in Soils by Cone Penetration Test," accepted for publication in the Journal of Geotechnical Engineering, American Society of Civil Engineers

Masood, T., Mitchell, J. K., Lunne, T., and Hauge, E. (1988), "Joint U.C. Berkeley and Norwegian Geotechnical Institute In-Situ Testing at Hamilton Air Force Base and Bay Farm Island, California," Department of Civil Engineering, University of California, September 1988

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Salgado, R. (1993), "Analysis of Penetration Resistance and Determination of the Stress State in Sands," Ph.D. Dissertation in Civil Engineering, University of California, Berkeley

Sisson, R. C. (1990), "Lateral Stresses on Displacement Penetrometers," Ph.D. Dissertation in Civil Engineering, University of California, Berkeley

Tseng, Dar-Jen (1989), "Prediction of Cone Penetration Resistance and its Application to Liquefaction Assessment," Ph.D. Dissertation in Civil Engineering, University of California, Berkeley

IV. PARTICIPATING SCIENTIFIC PERSONNEL

All Scientific personnel who participated in the research on this project are listed below. Financial support in varying amounts was provided to all of them except Dr. Coutinho. Advanced degrees earned by graduate students are indicated.

James K. Mitchell	-	Principal Investigator
Roberto Q. Coutinho	-	Associate Professor at the University of Pernambuco, Brazil and Visiting Scholar at Berkeley, 1990-92
Michele Jamiolkowski	-	Professor, Polytechnic University of Torino, Italy
Christine A. Human	-	received Ph.D. degree, 1992
Tahir Masood	-	received Ph.D. degree, 1990
Mairav Ravin	-	received M.S. degree, 1992
Salah Sadek	-	to receive Ph.D. degree, 1993
Rodrigo Salgado	-	to receive Ph.D. degree, 1993
Ray Shilling	-	received M. Eng. degree, 1990
Richard C. Sisson	-	received Ph.D. degree, 1990
Dar-Jen Tseng	-	received Ph.D. degree, 1989
Tajma Vaughns	-	received M.S. degree, 1988